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ELEMENTS OF THE THEORY UNDERLYING THE DISINFECTION OF WATER BY ULTRA VIOLET LIGHT[1]

By Gordon M. Fair, S.B.[2]

The steadily increasing use of ultra violet light for the disinfection of water supplies, large and small, seems to indicate that the art is sufficiently well advanced to warrant a discussion of the theory upon which it is based. This theory, recruiting its hypotheses and proofs from the basic sciences of physics, chemistry, and biology, deals with the nature and general physical properties of ultra violet light and with the photoabiotic effects which it is able to produce, so far as any of these are related to the application of ultra violet light to water disinfection. It is hoped that an elementary discussion of this nature will be of interest to water works engineers, and that it will be instrumental in dispelling the clouds of mystery which enshroud to so many this most natural of all methods of water disinfection.

The advance in our knowledge of the theory of ultra violet light is due especially to Schumann, Lyman, and other physicists who investigated the spectroscopy of the ultra violet, and to Bovie and his coworkers, who reported upon its biological activities, while the list of names of those who have been connected with its scientific application to water disinfection includes those of many scores of French, German, and American workers.

Radiation. The word "light" is familiarly associated with the sensation of vision alone. If, however, the electromagnetic waves which produce the sensation of light when they fall upon the eye and therefore become *post facto* "light or luminous radiations" be allowed to fall upon an opaque body, the same may be warmed and the radiations become "radiant heat." If, on the other hand, they fall upon a living green leaf or a photographic plate, they may produce chemical changes and thus become "actinic" or "chemical" rays. All three names—luminous, heat, or actinic radiations—may therefore be given to the same wave train, depending upon the effects which it is able to produce, and the term "light" which, strictly speaking, would apply only to radiations exerting the sensation of light, is used in a figurative sense to include the entire range of radiations which are alike in their general properties. But while the rays are traveling through space there is neither heat, light, nor chemical activity—merely wave motion. The frequency of this motion is inversely proportional to the wave length, permitting a constant velocity of travel of 300,000 kilometers or 186,000 miles per second. Waves which differ in their frequency differ to some extent in the degree of their power to produce heat, light, or chemical activity. The degree of this power is detected by the vibrations which they set up in the objects upon which they fall, just as when a note played on a musical instrument causes the same note on a neighboring stringed instrument to sound. It is merely due to a special property of the eye, therefore, that some of the radiations excite the sensations of light while others do not. Waves vibrating at less than 392,000,000 vibrations per second are too slow to affect the eye or produce chemical changes; they are called dark-heat-waves, while those vibrating more than 757,000,000,000 per second are too rapid to act upon the eye, but may affect chemicals; they are called actinic or ultra violet waves. The activity of the latter in bringing about chemical changes in both living and lifeless matter may be likened to the effect produced by singing its own note into a resonant tumbler, making it vibrate, shiver, and even break into pieces. The waves between the two limits of frequency given constitute the luminous radiations which produce a sensation of light upon the eye.

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[1] Discussion of this paper is requested and should be sent to the Editor.

[2] Instructor in Sanitary Engineering, Harvard University, Cambridge, Mass.

If a beam of monochromatic light be passed through a slit, the light issuing through the slit being caused to pass through a glass prism, it will be refracted and an image of the same color as that of the original beam of light will appear at some place on a screen held parallel to one side of the prism. If now a beam of white light be made to take the same path, it will form a number of colored images or a many colored band of light, each colored image of the slit being arrayed in the order of the frequency of its waves, the slowest ones (the red waves) being least refracted and the quickest ones (the violet waves) being most refracted. Between these limits we have the other colors of the rainbow, forming together the visible part of the spectrum. But the spectrum extends beyond the images of the visible rays. The slower invisible dark-heat-rays, being less refrangible, appear beyond the red, forming the infra red end of the spectrum; they are detected by a thermometer or other sensitive heat measuring device. The more rapid, invisible, actinic rays, being more refrangible, appear beyond the violet, forming the ultra violet end of the spectrum; they are detected by a photographic plate or by fluorescence.

It is not usual to define the range of a wave train by the limits of its vibration frequencies. The wave lengths (λ) of the train, which, since the velocity of travel is a constant, vary inversely as the vibration frequencies, are used in their stead. The unit of wave length chosen is sometimes the millimeter, sometimes the micron ($1\ \mu = 0.001$ millimeter), but ordinarily the Angstrom unit (1 Angstrom unit = 0.0000001 millimeter = $0.0001\ \mu$). Table 1 gives the wave lengths of a number of radiations.

TABLE 1

Wave lengths of some radiations

	Angstrom units λ
Shortest waves observed by Lyman about	900
Schumann waves	1000
Shortest visible violet waves	3800
Violet about	4000
Blue	4500
Green	5000
Yellow	5800
Red	6500
Longest visible red waves	7500

Beyond the longest heat waves and below the shortest ultra violet waves there are a multitude of other electromagnetic radiations, such as the wireless waves, which are measured in hundreds of meters, and the Röntgen and gamma rays, which are measured in tenths or hundredths of an Angstrom unit.

Transmission. If the object upon which a train of waves falls is not capable of resonant vibration with the waves, they pass through the object, which is then said to be transparent to light of the wave lengths in question. No substance is transparent to radiations of all wave lengths—indeed, such a substance would be invisible. White fluorite, perhaps the most transparent substance known, allows the passage of heat, luminous, and actinic rays. Crystal alum is not transparent to heat rays but permits the passage of luminous and actinic rays. Silver leaf thick enough to be opaque to luminous radiations passes ultra violet rays, while thin opaque pieces of vulcanite will allow radiant heat to pass. In general, matter decreases in transparency from the visible to the extreme ultra violet as the wave lengths decrease, until even highly rarified gases are opaque. When we pass beyond the light region, however, we find that as we approach the Röntgen and gamma rays ($\lambda = 0.1$ to 0.01 Angstrom units) this condition is reversed and that matter increases in transparency as the wave lengths decrease until in the region of the gamma rays even several centimeters of lead are transparent.

Absorption. If now a wave train falls upon an impervious body, i.e., one which is capable of resonant vibration with it, the progress of the train is arrested and the waves are either reflected or absorbed. The absorbed energy will effect a rise in the temperature of the body or other changes of a chemical or physical nature.

Absorption of ultra violet light by solids. The absorption of ultra violet light by solids, liquids, or gases is of prime consideration in its application to water disinfection. The source of ultra violet light is usually protected by a transparent envelope from direct contact with the water and the selection of some suitable material will influence qualitatively and quantitatively the radiations obtained as shown in table 2.

The selection of the protecting material is limited by: (1) its transparency to high frequency vibrations; (2) its ability to withstand immersion in water; and (3) its behavior under exposure to high temperature radiations from the source of light. Present experience favors the use of fused quartz. This mineral is obtainable in large homogeneous masses, is easily workable, and is extremely resistant to heat and water. The melting point of quartz is about 1700°C. Its linear coefficient of expansion is 0.39×10^{-6} cm. per degree Centigrade per centimeter as compared with 7.8×10^{-6} for glass and 7.5×10^{-6} to 13.7×10^{-6} for crystal quartz. It is transparent at all temperatures up to 900°C., when it changes to crystalline quartz or tridymite, an opaque mineral. The working temperatures, however, seldom exceed 300°C.

Absorption of ultra violet light by liquids. Quantitative measurements of the absorption of ultra violet light by water have been made by Kreusler, who apparently used a depth of two centimeters and found that 14.2, 24.5, and 68.9 per cent of radiations shorter than $\lambda = 2000$, 1930, and 1860 respectively were absorbed by this

TABLE

Absorption of ultra violet rays by solids

SUBSTANCE	THICKNESS	PER CENT ABSORBED	WAVE LENGTH, ANGSTROM UNITS	AUTHORITY
	mm.			
Common glass		100.0	3500	Lewis
Crown glass	10.0	Very strong	3100	Lyman
English borosilicate crown	2.0	100.0	2970	Zschimmer
Uviol glass	10.0	50.0	3050	Zschimmer
Uviol glass	1.0	50.0	2800	Zschimmer
Uviol flint	2.0	100.0	2850	Zschimmer
Uviol crown	2.0	100.0	2800	Zschimmer
Iceland spar	10.0	50.0	2800	Pflüger
Iceland spar	10.0	97.0	2140	Pflüger
Crystal quartz	10.0	5.8	2220	Pflüger
Crystal quartz	10.0	8.0	2140	Pflüger
Crystal quartz	10.0	16.4	2030	Pflüger
Crystal quartz	10.0	32.8	1860	Pflüger
Crystal quartz	2.0	100.0	1600	Lyman
Crystal quartz	0.2	Quite transparent	1450	Lyman
Fused quartz (probably impure)	2.8	100.0	2000	Pflüger
Fused quartz (pure)		Quite transparent	< 1850	Lyman
Rock salt		4.5	2800	Pflüger
		30.0	1860	Pflüger
Fluorite	10.0	20.0	1860	Pflüger
Topaz	1.5	100.0	1575	Lyman
Gypsum	1.0	100.0	1650–1700	Lyman
Colemanite		100.0	1750	Lyman
Alum	1.0	100.0	1750	Lyman

TABLE 3

Absorption of Ultra Violet Light by Water

DEPTH	PER CENT ABSORBED	WAVE LENGTH, ANGSTROM UNITS	INCREASED DEPTH PER 100 ANGSTROM UNIT INCREASE IN WAVE LENGTH	AUTHORITY
cm.				
0.05	100	1729		Lyman
2.90	100	1860	2.21	Kreusler
8.10	100	1930	7.43	Kreusler
14.10	100	2000	8.57	Kreusler

depth of water. Lyman found that 0.5 millimeter of water cut off the spectrum at 1729 Angstrom units. If we apply to these results Lambert's law that each layer of equal thickness absorbs an equal fraction of the light which passes it, we obtain the figures given in table 3.

These results show clearly that with increased wave length the depth of water which will absorb all the rays is materially extended. Unfortunately, however, there are no accurate data on wave lengths greater than 2000 Angstrom units. If, however, the increased depth per 100 Angstrom unit increase in wave length were constant after passing 2000 Angstrom units, it would take 43 centimeters of water to absorb all waves shorter than $\lambda = 2500$ and 86 centimeters or 2 feet 10 inches of water to absorb all wave lengths less than $\lambda = 3000$. The actual depth would apparently be even greater. As the figures in table 3 refer to experiments made on pure water, a slight allowance must be made under practical conditions for the color and the turbidity of the water supply which is to be treated, the disinfecting value of the light varying with colors of different magnitude and tints and turbidities of different amounts and fineness. Grimm and Weldert, for example, found that turbidities due to milk had a very much smaller coefficient of absorption than turbidities due to clay. It has also been ascertained that yellow tints are less transparent than green ones. From experiments made with water relatively rich in coloring and suspended matter, the author is inclined to believe that the colors and turbidities of filtered waters are usually not sufficiently high to influence the results materially.

Absorption of ultra violet light by gases. The ultra violet radiations of the sun are of very feeble physical energy, because we receive them only after they have been filtered through the atmosphere which surrounds our earth to the depth of about 14,000 meters. Miethe and Lehman determined the limit of the solar spectrum at various altitudes from near sea-level to 4560 meters and arrived at the surprising result that the last trace of light action was independent of altitude at $\lambda = 2912$. Their conclusions were confirmed by Wigand who at a height of 9000 meters with about two-thirds of the mass of air under him found the last trace of the sun's spectrum at $\lambda = 2897$ the same as on the earth's surface. These results would indicate that the atmosphere must either possess a very steep absorption curve or that the absorbing medium is confined to the upper layers of the air.

The absorption of various gases and vapors is given in table 4. From a study of table 4 it appears as if the absorption of ultra violet light by air is mainly due to the presence of oxygen in the air and that if necessary the source of light may be surrounded by hydrogen in order to lessen the absorption of the shortest waves emitted.

TABLE 4

Absorption of Ultra Violet Light by Gases and Vapors

GAS OR VAPOR	DEPTH	PER CENT ABSORBED	WAVE LENGTH ANGSTROM UNITS	AUTHORITY.
Air	0.05 mm.		< 1600	Schumann
	0.5 mm.	100.0	1630	Schumann
	9.1 mm.	100.0	1710	Lyman
	8–15.0 mm.	100.0	1780	Schumann
Dry air free from CO_2	20.45 cm.	8.8	1860	Kreusler
	20.45 cm.	Extremely small	1930	Kreusler
Oxygen	0.91 cm.	100.0	1760	Lyman
	20.45 cm.	32.5	1860	Kreusler
	20.45 cm.	6.2	1930	Kreusler
	20.45 cm.	Negligible	2000	Kreusler
Nitrogen	20.45 cm.	Very small	< 1620	Schumann
	20.45 cm.	2.2	1860	Kreusler
Carbon dioxide	0.91 cm.	100.0	1760	Lyman
	20.45 cm.	13.6	1860	Kreusler
Ozone		Negligible	In extreme ultra violet	Schumann
Helium	0.91 cm.	Not observable	1250	Lyman
Argon	0.91 cm.	Not observable	1250	Lyman
Hydrogen	0.91 cm.	Not observable	1250	Lyman
Water vapor in ordinary concentrations		Negligible	1900	Lyman

If we apply Lambert's law to the data relating to air, we obtain the figures in table 5.

Again, if the increased depth for each increase in wave length progressed as between λ = 1780 and λ = 1860, it would require a column of air 3.5 meters deep to absorb all waves less than λ = 2000, and a column 28.9 meters deep to absorb those less than λ = 3000. The actual increase is very much greater, as substantiated by Wigand's experiments described above. For the purpose of

TABLE 5

Absorption of Ultra Violet Light by Air

DEPTH	PER CENT ABSORBED	WAVE LENGTH, ANGSTROM UNITS	INCREASED DEPTH PER 100 ANGSTROM UNIT INCREASE IN WAVE LENGTH	AUTHORITY
cm.			*cm.*	
0.05	100	1630		Schumann
0.91	100	1710	1.08	Lyman
1.50	100	1780	0.84	Schumann
232.40	100	1860	289.00	Kreusler

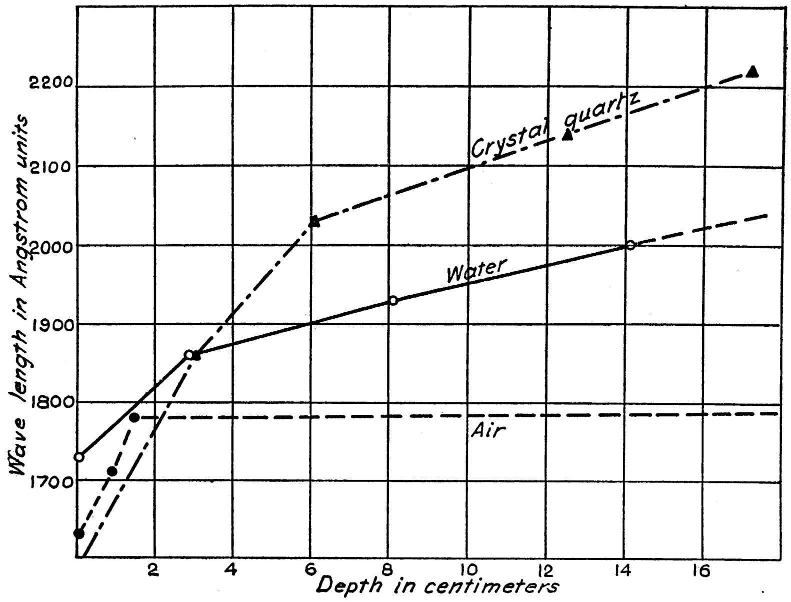

FIG. 1. ABSORPTION OF ULTRA VIOLET LIGHT OF DIFFERENT WAVE LENGTHS BY AIR, WATER AND QUARTZ

comparison the absorption values of air, water, and, in the absence of practical values for fused quartz, those for crystal quartz are plotted in figure 1.

Reflection of ultra violet light. We have seen that when a wave train falls upon a body capable of resonant vibration with it, the waves may be reflected instead of being absorbed, the amount of reflection varying with the composition and surface conditions of the object. The reflection of ultra violet light may be of value as there is no method of preventing the waste of a considerable amount of radiation in the application of this light to water disinfection. Up to the present time, however, no serious efforts have been made to utilize the reflecting power of metals. Table 6 has been prepared from Lyman's summary of past investigations.

TABLE 6

Reflection of ultra violet light by metals

DESCRIPTION	PER CENT OF RADIATIONS OF GIVEN WAVE LENGTH REFLECTED				TREND OF REFLECTION CURVE AT LAST POINT	AUTHORITY
	3800	2573	2510	2000		
Fresh silver mirror	4 (3160)		34.1		Upward	Hagen and Rubens
Silver			25 (2500)	18 (2265)		Minor
Platinum			33.8	28 (probable)	Downward	Hagen and Rubens
Platinum		37.1				Meier
Gold	Approx. minimum		38.8		Upward	Hagen and Rubens
Gold		27.6				Meier
Copper	Approx. minimum		25.9		Slightly upward	Hagen and Rubens
Nickel			37.8		Downward	Hagen and Rubens
Nickel		30.7				Meier
Iron			32.9		Downward	Hagen and Rubens
69 Al + 31 Mg	83		67		Downward	Hagen and Rubens
66 Cu + 22 Sn + 12 Zn.	60		40		Sharply downward	Hagen and Rubens
60 Cu + 30 Sn + 10 Ag.	60		40		Sharply downward	Hagen and Rubens
41 Cu + 26 Ni + 25 Sn + 8 Fe + 1 Sb	50		35.8		Sharply downward	Hagen and Rubens
68.2 Cu + 31.8 Sn	56.4 (4000)		29.9 (2500)	18 (prob-)able)		Minor
Wood's Alloy	56.6 (2747)	52.7				Meier

The differences between Meier's values and those of Hagen and Rubens may be ascribed to surface conditions. Unfortunately there is no information relating to the reflection of wave lengths shorter than those listed above.

Ultra violet light emission spectra. The commercial application of ultra violet light to water sterilization is closely linked to the advances made in the study of the spectra of gases and solids with relation to their wealth in ultra violet radiations. We have seen that when light of an infinite number of colors is passed through a spectroscope the infinite number of overlapping images forms a continuous spectrum. If, however, only a finite number of colors is used, the images will not overlap and a discontinuous spectrum will be formed. When the body radiating energy consists of an incandescent solid or liquid, it appears to send out an infinite number of radiations and the spectrum formed is continuous, although not necessarily equally bright throughout. A gas or vapor, on the other hand, seems to emit only a few distinct lines of light producing a discontinuous or a line spectrum. When the gas or vapor is put under pressure and the temperature is increased, the lines are broadened into the bands of a discontinuous band spectrum. The electric spark between metallic electrodes gives lines due both to the terminals and to the surrounding atmosphere. When, however, a spark passes through a partially exhausted tube, the luminosity is confined to the gas and the metallic lines disappear. The spark and arc between metallic terminals were used as the first sources of ultra violet light. Finsen, for example, used the iron arc with great success. The development of water disinfection, however, was based upon the invention of the quartz mercury vapor electric lamp as a result of the discoveries of Way, Hewitt, and Kuch. In 1860 Way discovered the arc between mercury electrodes a source very rich in ultra violet light. The heat generated by the arc, however, evaporated the mercury. To prevent the escape of the vapors, Cooper Hewitt enclosed the arc in a glass vacuum tube and provided cooling chambers to permit the condensation of the vapor at the terminals. A glance at table 2 will show that glass does not permit the passage of the more refrangible rays and it remained for Kuch to enclose the arc in quartz, thus producing the quartz mercury vapor electric lamp, the present source of ultra violet light used for water disinfection. Since the arc is formed in vacuo, the metallic mercury evaporates and fills the tube under a pressure of approximately one atmosphere. The values for the mercury arc spectrum determined by Wolff are given in table 7.

The spectrum of the mercury arc is dominated by the great line at λ = 1849.57, which explains the fact that a short intimate contact with the light in a thin film accomplishes as much as a long exposure at a greater distance from the light. With a lamp made entirely of quartz, Lyman places the limit of its spectrum at 1774.9 Angstrom units. He ascribes this result to the absorption of the quartz and the absorption of the dense mercury vapor itself. It is, therefore, essential to keep the diameter of the luminous tube of the quartz lamp and the thickness of the envelope to a minimum. The absorption of the light by the mercury vapor itself explains the fact that the broad band at λ = 1849.57 is always strongly reversed; the width of the whole band is usually about 30 or 40 units and that of the reversed portion is about 6 units. This self reversion which results in a dark line within the band is ascribed to the circumstance that a vapor or gas will absorb those radiations which it can itself most readily emit. A study of figure 1 with a view of determining the maximum depth of water which can be reached by the great line at λ = 1849.57 shows that it is completely absorbed by approximately 2.5 centimeters of water or by 3.0 centimeters of quartz. The combined thickness of quartz and water must therefore not exceed approximately 2.5 centimeters, if this line is to be utilized. It does not necessarily follow, however, that an apparatus based upon these limits presents the only solution of the problem. If we consider the next line (λ = 1942.52), for example, we find that it is completely absorbed by only 9 centimeters of water and that the absorp-

TABLE 7

Emission Spectrum of Mercury Arc

WAVE LENGTH IN ANGSTROM UNITS	RELATIVE INTENSITY	WAVE LENGTH IN ANGSTROM UNITS	RELATIVE INTENSITY
1402.72	6	1849.57	> 100
1435.63	2	1942.52	10
1650.17	8	1973.20	4
1672.75	5	1973.98	5
1675.55	4	1988.07	1
1774.95	5	2002.90	2
1832.60	4	2028.30	5
		2053.70	8

tion of the quartz, which will seldom exceed 0.3 centimeter in thickness, is not more than 7 per cent. A proportionate increase in the time of exposure of water 8 centimeters in thickness may therefore equal a shorter exposure in thinner films. A similar method of reasoning may be applied to greater wave lengths, and explains why in practice considerable depths of water can be treated with good results.

Photoabiotic phenomena. The statement that sunlight is the cheapest and most common disinfectant has almost become a scientific platitude. The nature of the germicidal action of the sun's rays is, however, not equally well known. A critical study of the subject shows that the destructive power of the sun's spectrum does not begin until the blue-green, that it reaches a maximum in the blue-violet, and extends beyond. The disinfecting value of sunlight is, therefore, ascribed to the photoabiotic power of the waves of higher vibration frequency. The limit of the sun's spectrum on the earth's surface is soon reached at $\lambda = 2900$ and other sources of light are, therefore, used to determine the effect of rays of short wave lengths upon the living organism.

The mechanism of cell destruction. It is found that the destructive power of light increases in general with the vibration frequency from the visible into the extreme ultra violet, where it is limited (at $\lambda = 1600$ approximately) by the fact that light of shorter wave lengths cannot penetrate sufficiently far into the living cell to materially affect its life processes. The photoabiotic action of ultra violet light furthermore seems to follow very closely Talbot's photochemical law that the amount of chemical change effected is proportional to the product of the intensity of the light and the length of exposure. It differs from this law only in that, when the exposure is interupted, the chemical changes produced in each exposure are additive while the photoabiotic changes are so only when the time elapsing between exposures is not sufficiently great to permit the organism to exert its power of repair. It is found that the rate of recovery from ultra violet radiation follows approximately the "die-away" curve, so that the percentage increase in the number of recovering organism is constant for each unit interval of time elapsing between exposures. The statement is often made that ultra violet radiations produce cytolysis through the absorption by the organism of a toxin produced photochemically in the surrounding medium rather than through direct action upon the living cell.

Experiments, however, have shown that, for example, the amount of hydrogen peroxide, which is claimed to be the destructive agent in the disinfection of water by this method and which is formed in water exposed to ultra violet light, is not sufficient to produce cytolysis. On the other hand, it can be shown that when a number of organisms are suspended in the same medium and only a few of them are exposed to the rays the latter alone will be cytolized, while those protected from ultra violet radiations, either by being out of the cone of light or by being protected by a small piece of suspended matter, remain unharmed. This would be impossible if the lethal agent were produced in the medium and not in the organism itself.

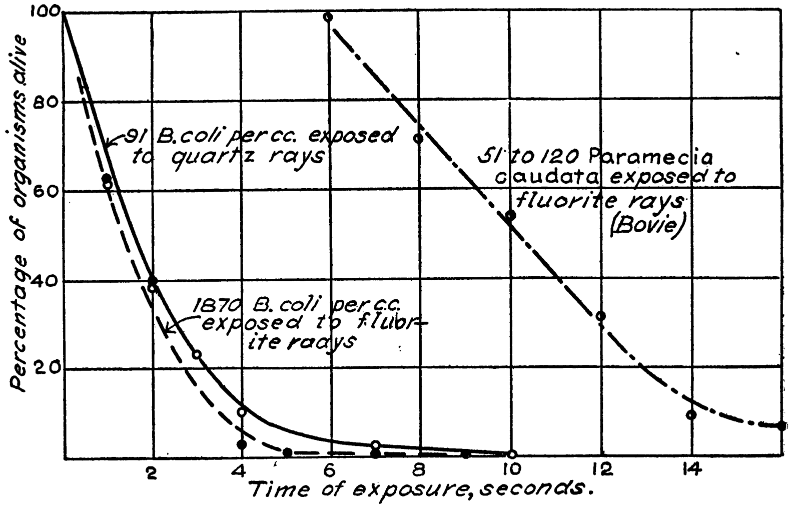

Fig. 2. Death Curve of Organisms Exposed to Ultra Violet Light

The curve of disinfection illustrated in figure 2 suggests, however, that the mode of death through exposure to high frequency vibrations is similar to that through poisons, heat, or drying. The exact shape of the curve depends upon the resistance of the individual organisms and their position in the medium exposed to the light. The initial lag in the "die-away" curve of the larger paramecia obtained by Bovie is to be expected. It is noteworthy that the number of cells dying in a given time interval is approximately proportional to the number of cells surviving; that, therefore, the rate of disinfection within practical limits is independent of the number of organisms present. The steepness of the curve is greatly influenced by the method of exposure. If the medium in which the organisms are suspended is stirred constantly, the chance of direct radiation is increased and the slope of the resulting curve of disinfection is very much greater. This fact explains the advantage of designing apparatus in such a manner as to maintain a vigorous stirring of the water which is to be disinfected.

The exact mechanism of cell destruction is by no means thoroughly understood. We know, however, that the rays must be absorbed in order to produce cytolysis and that seemingly the action is due to accelerated catabolism which, if exposure is continued, causes the death of the organism within a short space of time, after which photochemical processes seem to complete the destruction and dissolution of the cytoplasm. This theory is substantiated by the departure of the photoabiotic action of the rays from Talbot's photochemical laws in that an organism which has not been exposed too long may recover from the destructive effects of the rays and in some cases resume its normal life process of growth and reproduction.

After growths. The disinfection of water supplies and swimming pools by chemicals sometimes leads to a rapid increase in the number of those organisms which, due to some cause or other, escape destruction. In the clear field presented for growth, they multiply rapidly and may even exceed the bacterial count obtained before disinfection. Several factors may influence the survival of these living cells: (1) naturally greater resistance and spore formation; (2) protection afforded by particles of foreign matter; and (3) incomplete disinfection. Except under the second condition, the use of ultra violet light seems to present a distinct advantage over other methods of disinfection. It is claimed that, due to greater transparency, spores are more easily killed by light than vegetative forms, which accounts for the fact that enormous numbers of B. subtilis, which organism in the microscopic world is the counterpart of the proverbial nine-lived cat, are readily destroyed by quartz rays. The effect of incomplete disinfection by ultra violet light is illustrated in figure 3.

A consideration of the results obtained with wave lengths of $\lambda = 2800$ leads Bovie to the following conclusions: (1) the length of exposure required for inhibition is only about one-thirtieth of that required to produce cytolysis; (2) the duration of the inhibition increases with increased exposure; and (3) the inhibition is followed by an acceleration in reproduction. A study of the rate of repro-

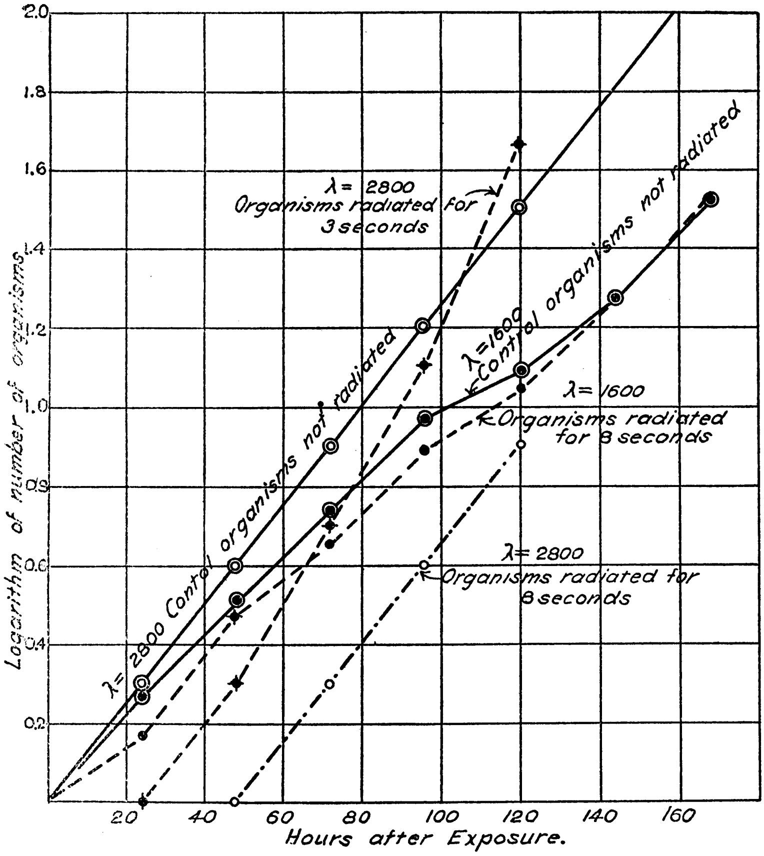

FIG. 3. EFFECT OF ULTRA VIOLET LIGHT OF DIFFERENT WAVE LENGTHS (λ = 1600; λ = 2800) UPON THE RATE OF DIVISION OF PARAMECIUM CAUDATUM (AFTER BOVIE)

TABLE 8

Aftergrowths of B. Coli Exposed to Quartz Radiations

SAMPLE NUMBER	TIME OF EXPOSURE	ORGANISMS PER CUBIC CENTIMETER			REPRODUCTION FACTOR
		Before radiation	After radiation	After incubation for 48 hours at 37°C.	
	seconds				
1	0	42	42	10,100	7.91
2	2	42	24	1,080	5.49
3	4	42	11	128	3.54

duction of organisms surviving radiations of λ = 1600, on the other hand, suggests that these rays, although more destructive in a given length of time, are unable to penetrate to the nucleus of the cell in the same degree as light of longer wave lengths and that reproduction is therefore not inhibited except when the organism is killed. As a result of these observations, a source of light emitting rays of varying frequency suggests itself as the best disinfecting agent. This is further substantiated by experiments made under the author's direction with B. coli in water to which a small amount of nutrient broth had been added as shown in table 8.

The figures in the last column were obtained by assuming a geometrical increase in the number of organisms and calculating the number of generations or cell divisions which would have occurred had each surviving organism reproduced at the same rate. The number and type of organisms developing after disinfection depend naturally upon the composition of the surrounding medium and vary with waters of different physical, chemical, and biological content.

Summary. The most important points of the theory underlying the application of ultra violet light to water sterilization may be summed up as follows:

1. The photoabiotic properties of light are due to the action of high frequency vibrations extending from the blue-green (λ = 4800) to the extreme ultra violet (λ = 1600).

2. Matter decreases in transparency to light from the visible to the extreme ultra violet as the wave lengths decrease until even highly rarified gases are opaque.

3. Fused quartz is at present the solid most readily adapted for use with ultra violet radiations. It permits the passage of light of wave lengths as small as λ = 1800, melts at about 1700°C., has a linear coefficient of expansion of 0.39×10^{-6} centimeter per degree Centigrade per centimeter, and is obtained pure in large quantities.

4. Water is transparent to a considerable depth and can therefore be disinfected by the radiations emitted by a quartz mercury vapor electric lamp.

5. The absorption of ultra violet light by air is due to its oxygen content but is not sufficiently great to be of consideration outside of the laboratory.

6. The reflection of ultra violet light by metals warrants a greater effort for its utilization.

7. The quartz mercury vapor electric lamp emits radiations as small as 1800 Angstrom units in wave length. It is, therefore, possible to utilize the great line at $\lambda = 1850$ for short exposures and intimate contacts while making use of the rays of smaller vibration frequency for longer exposures at greater distances.

8. The destructive power of light begins in the blue-green ($\lambda = 4800$) and increases with the vibration frequency up to $\lambda = 1600$ approximately.

9. Talbot's photochemical law, if correctly interpreted, is applicable to photoabiotic phenomena.

10. The rate of recovery from ultra violet radiations follows approximately the "die-away" curve.

11. High frequency vibrations of light act directly upon the organism and not indirectly through the medium.

12. The mode of disinfection through light, poisons, heat, and desiccation is very similar.

13. The destruction of the cell is due to increased catabolic changes.

14. Aftergrowths are limited by the inhibition of organisms surviving exposure to ultra violet rays.

15. Light of short wave lengths ($\lambda = 1600$) is more effective in destroying organisms but less effective in decreasing the rate of reproduction of those organisms which are not killed by exposure.

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Note: Only a few of the many important contributions to the literature of ultra violet light are given below.

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